# The fluid dynamics of river dunes: A review and some future research directions

Jim Best

Earth and Biosphere Institute, School of Earth and Environment, University of Leeds, Leeds, UK

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[1] Dunes are present in nearly all fluvial channels and are vital in predicting flow resistance, sediment transport, and deposition within many rivers. Progress in understanding the fluid dynamics associated with alluvial dunes has been significant in the last 15 years and has witnessed huge advances in field, laboratory, and numerical investigations. Progress has been made in detailing the principal features of mean and turbulent flow over asymmetric dunes that possess flow separation in their leesides and how these forms affect both downstream boundary layer structure and stress partitioning over the dune. Additionally, the links between sediment transport over dunes and instantaneous coherent flow structures are being increasingly understood, with the feedback of dune three-dimensionality upon flow and sediment dynamics over these bed forms beginning to be recognized as vital. Such research now provides an outstanding background for beginning to address areas of greater complexity that will enable a fuller understanding of these important natural features. This review paper summarizes the principal features of mean and turbulent flow over alluvial sand dunes. Five areas are then highlighted and discussed as a possible focus for future research: (1) the influence of dune leeside angle upon flow processes in the dune wake and downstream flow field, (2) the influence of three-dimensionality in dune shape upon the generation of turbulence and distribution of bed shear stress, (3) flow field modification resulting from bed form superimposition and amalgamation, (4) the scale and topology of dune-related turbulence and its interactions with sediment transport and the flow surface, and (5) the influence of suspended sediment on the dune flow field and dune morphology.

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## 1. Introduction

[2] River dunes are of central importance within many branches of environmental and engineering science in the practical management of contemporary river channels [*ASCE Task Force*, 2002, 2005], and adopt especial significance in the sedimentary record where dunes form the key building blocks of many ancient alluvial successions. As demands on land and water resources for human settlement grow, there is an increased need to manage many sizes of rivers in an effective and sustainable manner, and hence the prediction of flow, sediment transport and both bed and bank stability becomes of paramount importance for engineers, geomorphologists and planners. Such problems are especially acute in countries such as Bangladesh, where riverbank erosion, often driven by within-channel aggradation that is linked to the growth of dunes and larger bar forms [*Ashworth et al.*, 2000; *Best et al.*, 2005], can lead to very significant population displacement and loss of infrastructure and agricultural land [*Best et al.*, 2005]. The threat to infrastructure caused through sediment transport associated with dunes in the Rio Paraná, Argentina is highlighted by *Amsler and García* [1997], *Amsler and Prendes* [2000], and *Amsler and Schreider* [1999], who describe channel erosion near the city of Paraná as part of the disastrous floods of 1983 and 1992. In one region of the river, where the Paraná narrows to ∼1.5 km in width, a 2.4 km long subfluvial tunnel was built in 1968 and the depth of its placement was determined from regime theory, with a minimum cover thickness of 4m above the tunnel [*Amsler and García*, 1997]. However, the long duration of high floods in 1983 led to the formation of large dunes, up to 6.5 m in height and 320 m in length, that migrated through this river section. These large dunes caused temporary exposure of the tunnel to the flow over a distance of 250 m each time the trough of a large dune moved over the tunnel [*Amsler and García*, 1997; *Amsler and Schreider*, 1999], thus threatening its stability. Remedial actions were required to ensure the stability of the tunnel, involving placing trucks full of sediment within the tunnel to prevent uplifting during most of the flood. This reach is now an area that is receiving much study and monitoring to assess the longer-term changes in bed elevation and the hysteresis effects of dune morphology through floods.

[3] The deposits of river dunes also adopt great significance in many ancient sedimentary successions because


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they are one of the most common depositional bed forms, forming in a range of sediment sizes from silt and sand through to gravel [*Dinehart*, 1992; *Seminara*, 1995; *Best*, 1996; *Carling*, 1999; *Kleinhans*, 2001, 2002; *Carling et al.*, 2005]. Recent studies of subsurface alluvium also demonstrate that dunes can form the majority of the deposits of sandy braided rivers [e.g., *Best et al.*, 2003; *Bridge*, 2003], and can create heterogeneous and anisotropic permeability fields in the subsurface, thus complicating prediction of subsurface flow in both aquifers and hydrocarbon reservoirs [*Weber*, 1980, 1986; *Van de Graff and Ealey*, 1989; *Truss*, 2004]. For instance, grain sorting on the dune lee side [*Blom et al.*, 2003; *Kleinhans*, 2001, 2002, 2004] may be highly influential in creating anisotropic grain size and grain fabric that will strongly influence the later subsurface movement of fluids. Furthermore, experimental work has shown the critical role of bed forms, and particularly dunes, in influencing convective flow within the bed sediment that is generated by the differential pressure gradient caused by the bed form [*Thibodeax and Boyle*, 1987]. *Packman and Brooks* [2001], *Packman and Mackay* [2003], and *Packman et al.* [2000a, 2000b, 2004] also demonstrate the importance of bed forms in hyporheic exchange (the mixing of stream water with pore water beneath the sediment bed). They show the importance of dunes for both the clogging of the porous bed by finer grains, such as kaolinite, and that the exchange of solutes and colloids is also linked to the rate of bed form migration and scour, with faster moving bed forms reworking the bed and leading to a greater turnover of sediment.

[4] Additionally, the relationship between bed form size and the formative flow depth may be of great use in reconstructions of paleoflow depths, and recent attempts to summarize on the thickness of cross stratification and their original formative bed form heights have met with promising success [*Leclair*, 2002; *Bridge*, 2003]. Thus an understanding of how the processes of flow over dunes lead to erosion, transport and deposition, and the inverse problem in the rock record of deciphering the sedimentary structure to reconstruct flow processes, is essential to more complete interpretations. The dimensions and morphology of water-formed dunes established from theory and experiment, and tested on proposed megafloods on Earth [e.g., *Carling*, 1996; *Carling et al.*, 2002], have even been utilized to interpret the origin of dunes on Mars, erect hypotheses for discharge regimes on the Earth's planetary neighbor [*Burr et al.,*, 2004], and contribute to the debate on the role of catastrophic outburst floods on the Martian surface [*Baker and Milton*, 1974; *Baker*, 2001; *Burr et al.*, 2002, 2004].

[5] Recent years have seen spectacular progress in our knowledge of dune dynamics that has often been linked to significant advances in our ability to monitor flow and dune morphology in the laboratory and field, and the increasing sophistication of numerical modeling to capture not only the characteristics of the mean flow field but realistically simulate the origins and motions of coherent flow structures above dune beds. Although only a few years ago models of turbulent flow over dunes were thought not to be as "impressive as one might desire" [*ASCE Task Force*, 2002, p. 727], recent models [e.g., *Schmeeckle et al.*, 1999; *Shimizu et al.*, 1999; *Balachandar et al.*, 2002; *Yue et al.*, 2003, 2005a, 2005b; *Hayashi et al.*, 2003] have begun to produce detailed and realistic simulations of the instantaneous structure of flow over dune topography. These advances in laboratory, field and numerical modeling now leave us, as never before, in a position to make radical progress in quantifying, modeling and understanding the dynamics and kinematics of alluvial dunes. Significant advances in our understanding have been achieved through studies that have been concerned both with the origin of dunes [e.g., *Kennedy*, 1963, 1969; *Raudkivi*, 1966; *Fredsøe*, 1974, 1982; *Yalin*, 1977, 1992; *Richards*, 1980; *Nelson and Smith*, 1989; *McLean*, 1990; *Bennett and Best*, 1996; *Gyr and Kinzelbach*, 2004], their stability and transformations [*Leeder*, 1983; *Bennett and Best*, 1996; *Robert and Uhlman*, 2001; *Schindler and Robert*, 2004, 2005], uses in estimating bed load transport [e.g., *Engel and Lau*, 1980; *Mohrig and Smith*, 1996; *Vionnet et al.*, 1998] and their role in determining flow resistance [e.g., *Ogink*, 1988; *Yoon and Patel*, 1996; *Julien et al.*, 2002; *Wilbers*, 2004]. Additionally, these studies have been conducted both in increasingly sophisticated and quantitative laboratory studies [e.g., *van Mierlo and de Ruiter*, 1988; *Mendoza and Shen*, 1990; *Lyn*, 1993; *McLean et al.*, 1994, 1996, 1999a, 1999b; *Nelson et al.*, 1993; *Bennett and Best*, 1995; *Bennett and Venditti*, 1997; *Kadota and Nezu*, 1999; *Nelson et al.*, 2001; *Best and Kostaschuk*, 2002; *Maddux*, 2002; *Maddux et al.*, 2003a, 2003b; *Best*, 2005] and a growing quantification of dune form and process within the natural environment [e.g., *Kostaschuk et al.*, 1989; *Gabel*, 1993; *Julien and Klaassen*, 1995; *Kostaschuk and Church*, 1993; *Kostaschuk and Ilersich*, 1995; *Kostaschuk and Villard*, 1996, 1999; *Roden*, 1998; *Villard and Kostaschuk*, 1998; *Carling et al.*, 2000a, 2000b; *Best et al.*, 2001, 2005; *Williams et al.*, 2003; *Sukhodolov et al.*, 2004; *Parsons et al.*, 2005]. Recent excellent summaries on the dynamics and role of dunes are provided by an ASCE working group [*ASCE Task Force*, 2002, 2005] as well as by *Bridge* [2003]. These syntheses highlight that in order to more completely understand the dynamics of river dunes, a fuller appreciation is needed of the complex links between turbulence, bed morphology and sediment transport.

[6] The present review paper aims to achieve two goals: (1) to present a brief synthesis of the major features of flow, morphology and sediment transport associated with river dunes and (2) to use this synthesis to highlight five areas of recent/ongoing and future research that appear vital to evolve a more complete understanding of the fluid dynamics of river dunes. These key issues concern (1) the occurrence and fluid dynamics of low-angle dunes, (2) the influence of dune three-dimensionality in planform and cross-sectional morphology, (3) bed form superimposition, (4) the interactions of large-scale dune-generated turbulence with the flow surface, and (5) the influence of suspended sediment on dune form and flow.

## 2. Synthesis

[7] Flow over river dunes, that are asymmetric in cross-sectional form, possess an angle-of-repose leeside and are generated in a steady, uniform unidirectional flow, can be summarized as having five major regions [*McLean and

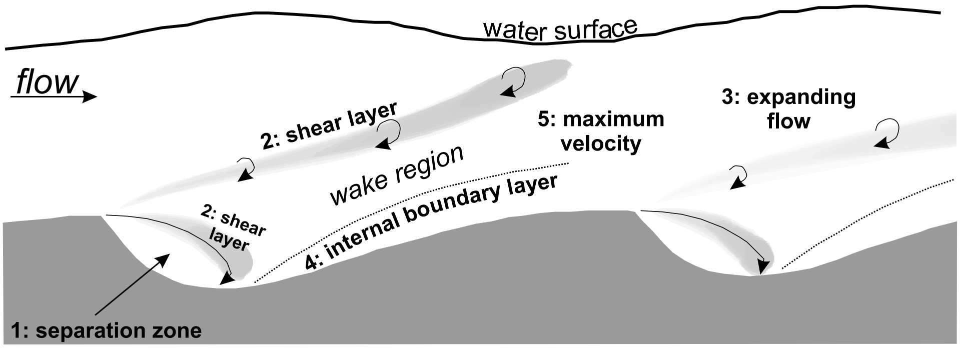


**Figure 1.** Schematic diagram of the principal regions of flow over asymmetrical, angle-of-repose dunes (see text for explanation).

*Smith*, 1979, 1986; *Nelson and Smith*, 1989; *McLean*, 1990; *Nelson et al.*, 1993; *McLean et al.*, 1994, 1999a, 1999b; *Bennett and Best*, 1995; *Maddux et al.*, 2003a; *Bridge*, 2003; *Kleinhans*, 2004] (Figure 1): (1) a region of flow separation is formed in the lee of the dune, with reattachment occurring approximately 4–6 dune heights downstream of the crest. (2) A shear layer is generated bounding the separation zone, which divides this recirculating flow from the free stream fluid above; large-scale turbulence is generated in the form of Kelvin-Helmholtz instabilities along this shear layer, and as the free shear expands, it creates a wake zone that grows and dissipates downstream. (3) A third region is one of expanding flow in the dune leeside. (4) Downstream of the region of reattachment, a new internal boundary layer grows as flow reestablishes itself and develops a more logarithmic velocity profile. (5) Maximum horizontal velocity occurs over the dune crest and bed shear stresses here may be sufficient to generate upper stage plane bed conditions: the exact nature of flow here will determine the rate and periodicity of sediment supply to the dune leeside and hence the nature of sediment sorting in the deposits of the leeside.

[8] This flow structure generated over asymmetric river dunes has many important implications for flow resistance, bed shear stress and sediment transport [*ASCE Task Force*, 2002, 2005; *Fedele and García*, 2001]. For instance, the differential pressures generated by flow separation and flow acceleration/deceleration associated with the dune form, generate a net force on the dune that is the "form drag": such form drag is in addition to grain roughness drag, and makes dune morphology (for instance, dune shape, height and the presence/absence of flow separation) critical in assessments of flow resistance and energy expenditure over dunes [*Maddux et al.*, 2003a, 2003b]. Additionally, predictions of sediment transport over dunes, a key aspect of many applications of dune research, relies on being able to estimate shear stress over the dune and link this to sediment transport equations [e.g., *Smith and McLean*, 1977a; *Villard and Kostaschuk*, 1998; *McLean et al.*, 1999a, 1999b; *Fedele and García*, 2001; *Kostaschuk et al.*, 2004]. Parameterization of the shear stress in such complex flows thus demands an appreciation of the mean flow field in order to account for the influence of dune form, bed form superimposition and leeside slope angle, and assess the effect of spatial averaging on estimates of shear stress [*ten Brinke et al.*, 1999; *McLean et al.*, 1999a; *Fedele and García*, 2001; *Wilbers and ten Brinke*, 2003].

[9] However, it has become increasingly well documented that the turbulent flow field over dunes is critical in determining instantaneous bed shear stresses [*Nelson et al.*, 1993, 1995; *McLean et al.*, 1999a], local bed load transport rates, and sediment suspension [*Nelson et al.*, 1995; *Cellino and Graf*, 2000] and therefore in controlling the form of the bed surface and water surface topography [*Bennett and Best*, 1995]. Turbulence over such classic, angle-of-repose dunes with a mean flow field as summarized above, is dominated by the influence of the flow separation zone and vorticity generated along the bounding shear layer. Several studies have illustrated the high Reynolds stresses present along this region in both laboratory experiments [*Nelson et al.*, 1993; *van Mierlo and de Ruiter*, 1988; *Bennett and Best*, 1995] and also in some field studies [*McLean and Smith*, 1979; *Kostaschuk*, 2000; *Roden*, 1998; *Best et al.*, 2001]. If the fluctuations in horizontal and vertical velocity at a point are decomposed into their deviations from the mean, this defines four quadrants: quadrant 1 [$+u'$ $+v'$], quadrant 2 [$-u'$ $+v'$], quadrant 3 [$-u'$ $-v'$], and quadrant 4 [$+u'$ $-v'$], where $u$ and $v$ are the horizontal and vertical components of velocity, respectively; the prime indicates the instantaneous deviatoric value from the mean, and an overbar indicates the time-averaged value of this component of velocity [i.e., $u = \overline{u} + u'$]. Positive values of vertical flow indicate flow upward and away from the bed. For a description of quadrant signatures associated with dunes, see *Nelson et al.* [1995], *Bennett and Best* [1995], and *Best* [1996]. Large-scale vorticity, generated as Kelvin-Helmholtz instabilities, is manifested as quadrant 2 events and arises both along the shear layer and at flow reattachment [*Bennett and Best*, 1995]. These coherent flow structures are advected with the mean flow, often reaching the flow surface and erupting as surface "boils" [e.g., *Jackson*, 1976; *Yalin*, 1992; *Babakaiff and Hickin*, 1996; *Best*, 2005], and may contain higher concentrations of sediment than the surrounding flow [*Kostaschuk and Church*, 1993; *Lapointe*, 1992, 1996; *Babakaiff and Hickin*, 1996; *Bennett and Venditti*, 1997; *Venditti and Bennett*, 2000].

## 3. Key Issues

[10] Although the brief synthesis above indicates the substantial advances that have been made in the last

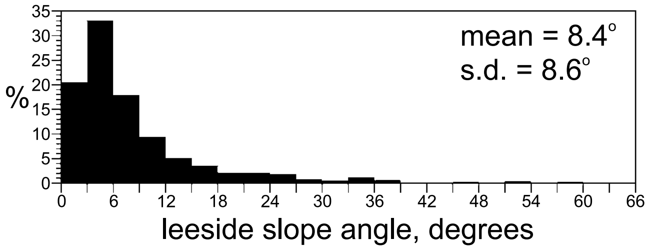


**Figure 2.** Histogram of leeside slope angle compiled from measurements of 1400 dunes in the Jamuna River, Bangladesh [from *Roden*, 1998; *Best et al.*, 2005].

15 years concerning fluid flow and sediment dynamics over dunes, much of this knowledge has been gained from studies involving simplified boundary conditions (for instance two-dimensional dunes under steady flows) that have not been able to investigate the more complex flow and morphology typical of all natural rivers [e.g., *Gabel*, 1993; *Mohrig and Smith*, 1996; *van den Berg*, 1987; *Carling et al.*, 2000a, 2000b; *Wilbers and ten Brinke*, 2003; *Bartholomä et al.*, 2004; *Wilbers*, 2004; *Parsons et al.*, 2005]. The sections below present brief reviews on five areas of complexity and thoughts on key research questions that require attention in order to yield a more complete understanding of natural alluvial dunes.

### 3.1. Occurrence and Fluid Dynamics of Low-Angle Dunes

[11] Much past modeling and research has concentrated on the dynamics of river dunes that have angle-of-repose leesides that generate flow separation and appreciable turbulence downstream [*van Mierlo and de Ruiter*, 1988; *Müller and Gyr*, 1983, 1986, 1996; *Mendoza and Shen*, 1990; *Lyn*, 1993; *Nelson et al.*, 1993; *McLean et al.*, 1994, 1996, 1999a, 1999b; *Bennett and Best*, 1995, 1996; *Kadota and Nezu*, 1999; *Shimizu et al.*, 1999; *Kostaschuk*, 2000]. Debate still exists as to the nature and cause of river dunes with low-angle leesides [*Smith and McLean*, 1977a, 1977b; *Kostaschuk and Villard*, 1996, 1999; *Best and Kostaschuk*, 2002; *Best et al.*, 2004; *Wilbers*, 2004], and the similarities and differences between the flow fields of high- and low-angle dunes. Data from the Jamuna River, Bangladesh (Figure 2) [*Roden*, 1998; *Best et al.*, 2005] and other large rivers [*ten Brinke et al.*, 1999; *Kostaschuk and Best*, 2005] show that low-angle dunes are common and may often represent the most abundant dune shape: it appears increasingly likely that many large rivers are characterized by dunes with leeside slopes lower than the angle of repose. *Roden* [1998] and *Best et al.* [2005] found the mean leeside angle of dunes in the Jamuna River to be 8.4° (Figure 2), while *ten Brinke et al.* [1999] show dunes in the Rhine and Waal rivers to have leeside slopes of between 2° and 8°, and that leeside slope increases with flow discharge through a flood hydrograph. *Harbor* [1998] also illustrated dunes in the Mississippi River that have low height:length ratios, with some compound dunes possessing smaller dunes migrating down their leeside [*Harbor*, 1998] (see section 3.3) that also indicates the probable lack of permanent flow separation in the leeside. *Smith and McLean* [1977a] reported spatially averaged profiles of downstream velocity over dunes in the Columbia River and noted that some dunes, which were more symmetrical in profile than dunes over which flow separation occurred in the leeside, possessed unseparated flow. *Atkins et al.* [1989] and *Johns et al.* [1993] also report the absence of permanent flow separation on the leeside of asymmetric sand dunes, with *Atkins et al.* [1989] reporting the presence of intermittent flow separation in the dune trough. Since flow resistance and energy expenditure associated with dune-covered beds is known to be intimately linked to the development and extent of flow separation in the dune leeside [*Ogink*, 1988], it becomes important to quantify the form of dunes and assess their role in influencing the flow field. The deposits of low-angle dunes may also be important in the sedimentary record, with low-angle dunes being characterized by much lower dip angles in their preserved foresets, possibly with superimposed smaller dunes that migrate down their leeside. Additionally, the low angle and different shape of these dunes, when compared to angle-of-repose dunes, may make the relationship between preserved foreset size and reconstructions of paleoflow depth [e.g., *Leclair*, 2002] far more problematic than predicted by current models that assume steeper leeside slopes.

[12] Recent laboratory and numerical modeling (Figure 3) [*Best and Kostaschuk*, 2002; *Best et al.*, 2004] illustrates the details of flow in the leeside of a low-angle dune that was scale modeled from a prototype in the Fraser River, Canada (Figure 3). Permanent flow separation is absent in the lee of these dunes, although intermittent flow separation was found to occur in the immediate leeside for a small percentage of the time (Figure 3) [*Best and Kostaschuk*, 2002]. Previous field studies have also suggested the absence of flow separation associated with dunes in both alluvial [*Smith and McLean*, 1977a, 1977b; *Kostaschuk and Villard*, 1996, 1999] and tidal environments [*Williams et al.*, 2003], although it is often very difficult, if not impossible, to measure very near the bed in many field studies. *Wilbers* [2004] suggests that flow separation may be present over low-angle dunes but that field, and possibly flume measurements, cannot be gained close enough to the bed to reveal regions of permanently separated flow. However, both experimental and numerical simulations show that flow separation does occur, but that it is a transient feature of flow. Additionally, there is a wide body of literature [e.g., *Azad*, 1996; *Azad and Kassab*, 1989] (Figure 3) that documents the occurrence of intermittent flow separation downflow from conical diffusers, in which the change in angle at the diffuser expansion is often less than 10°, and supports the contention that transient separation is present associated with low-angle alluvial sand dunes. *Hasbo* [1995] also

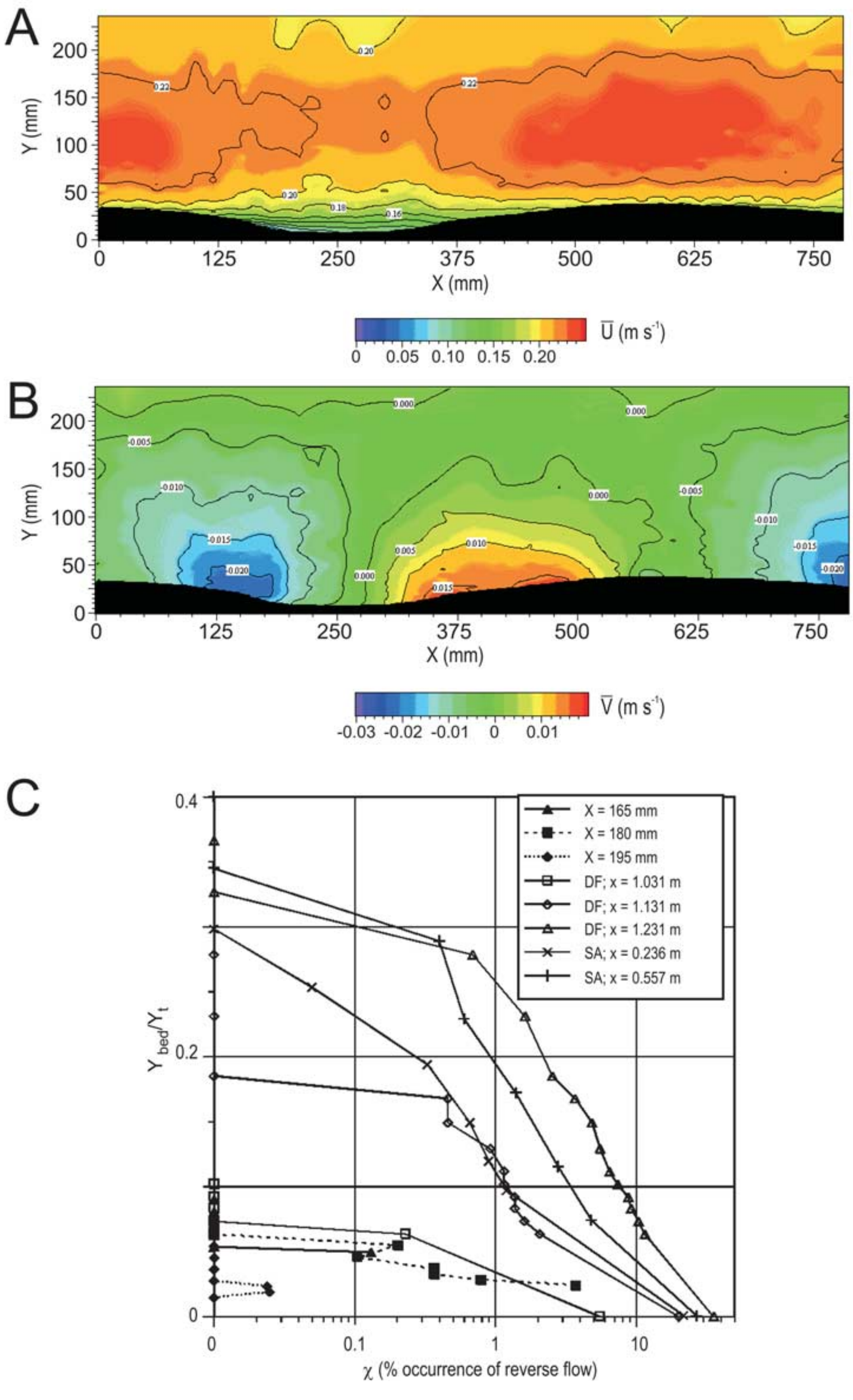


**Figure 3.** Characteristics of flow over a low-angle dune [after *Best and Kostaschuk*, 2002]. (a) Downstream flow velocity (m s$^{-1}$), (b) vertical flow velocity (m s$^{-1}$), and (c) plot of intermittency factor, against dimensionless height above the bed ($Y_{bed}/Y_t$, where $Y_{bed}$ is height above the bed and $Y_t$ is the flow depth upstream of the diffuser or at the dune crest) for profiles in the immediate dune leeside (X = 165–195 mm; see Figures 3a and 3b for location). Here $\chi$ is defined as the percentage of the time that flow at a point undergoes reverse (upstream) horizontal flow, and upstream flow was only present near the bed for profiles at X = 165, 180, and 195 mm. Also shown are the plots of $\chi$ given by *Dengel and Fernholtz* [1990] (DF) for flow at three distances along a flat plate in the region of transitory detachment and *Singh and Azad* [1995a, 1995b] (SA) for flow in a conical diffuser (at 0.236 and 0.557 m downstream of the diffuser entrance). From *Best and Kostaschuk* [2002].

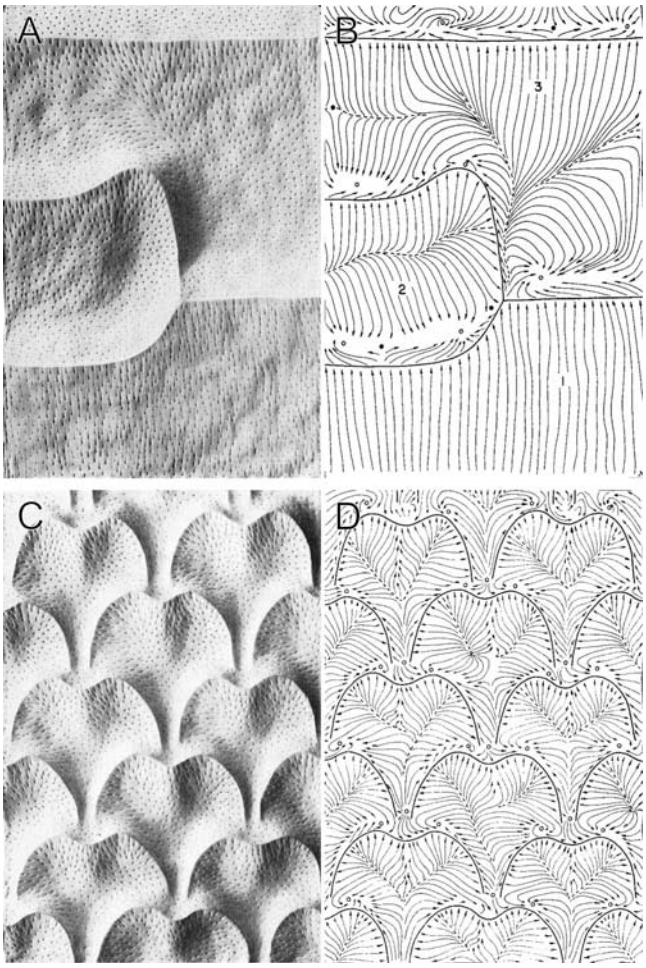


**Figure 4.** Flow over sinuous ripples [after *Allen*, 1968]. Flow is from bottom to top in each image. Figures 4a and 4c show plaster-of-Paris visualization of flow (see *Allen* [1968] for details) at the bed over (a) a simple ripple with a zigzag juncture and (c) bow-shaped linguoid ripples. (b and d) Bed streamlines constructed from the models shown in Figures 4a and 4c. These maps illustrate the complexity of flow over 3-D forms and the presence of flow separation associated with the leeside and also developing longitudinal vorticity associated with 3-D forms. In Figure 4b, flow over ripple 1 generates a closed separation zone with simple flow reattachment on ripple 2, whereas to the right side of ripple 1 the juncture generates an open separation zone that produces far more complex patterns of reattachment on downstream ripple 3.

indicates the lack of permanent flow separation over ridges with low-angle leesides that were placed both normal and oblique to the mean flow. Several key questions remain to be answered. First, under what range of conditions (flow, sediment flux) are high- and low-angle dunes present? Second, what are the temporal characteristics of flow, and possible intermittent separation, over a range of low-angle dunes (different shape and leeside angle), and does any large-scale turbulence reach the flow surface? (see later). Last, the question remains as to why dunes with low leeside angles are generated, and aspects of this are discussed below with respect to bed form amalgamation and the influence of high suspended sediment loads [*Smith and McLean*, 1977a].

### 3.2. Influence of Dune Three-Dimensionality

[13] In addition to most past research on the fluid dynamics of dunes being concerned with angle-of-repose dunes, virtually all work has dealt with morphologies that are essentially two-dimensional and have no 3D shape or curvature, a situation that is rare in natural river channels. The seminal early work of *Allen* [1968] beautifully illustrated the complex nature of flow separation and boundary layer recovery downstream from a range of bed form planform shapes. It is still instructive to revisit this text and find details of the flow field and bed streamlines over straight, skewed and curved bed forms (Figure 4). The experiments of *Allen* [1968] demonstrated that bed form three-dimensionality introduces considerable complexity into the flow, as compared to a 2-D counterpart, generating both flow-parallel and spanwise vorticity and complex convergence and divergence of flow.

[14] Although flow three-dimensionality is evident from this past work, and in all natural river channels, the issue of quantifying the 3D dune morphology and its influence on flow structure has not been addressed until recently. *Venditti et al.* [2005b] contend that all dune bed forms must eventually become three-dimensional, due to minor, transient excesses or deficiencies of sand being passed from one bed form to another. *Hasbo* [1995] presents results from both physical and numerical models to illustrate how the obliquity of the bed form crest, with respect to the mean flow direction, can significantly influence the flow structure in the bed form leeside, with the angle of the leeside slope also being critical (see section 3.1). Obliquity of the crest can influence the length of any separation zone and thus influence the magnitude of the leeside Reynolds stresses, drag coefficients and the dispersal patterns of sediment. *Maddux et al.* [2003a, 2003b] presented the first detailed study of flow over fixed 3D dunes in which the dune was two-dimensional across the flume width, but the height of the crest line varied, thereby introducing a 3D form with minima and maxima in crest line height and with nodes in between (Figure 5a). This work demonstrated that the maximum streamwise velocities were highest over the nodes rather than maxima in crest line height (Figure 5b), that turbulence over these 3D dunes was lower than over their 2D counterparts and that the sinuous crest lines were associated with the presence of secondary currents that were responsible for a large percentage of the momentum flux over the dune. *Zedler and Street* [2001] have also demonstrated the presence of longitudinal spanwise vorticity over 3D ripples while *Maddux et al.* [2003a, 2003b] also showed that, although the friction coefficients of 3D dunes were 50% greater than their 2D counterparts, the turbulence generated by 3D dunes was weaker than the 2D case, due to the generation of secondary flows over the 3D forms. *Maddux et al.* [2003b] also argued that form-induced stresses were established from these secondary currents and that these augmented the low Reynolds stresses present over the 3D dunes. Although the dunes studied by *Maddux et al.* [2003a, 2003b] are still relatively simple, they demonstrate a considerable complexity and several major differences compared to their 2D counterparts.

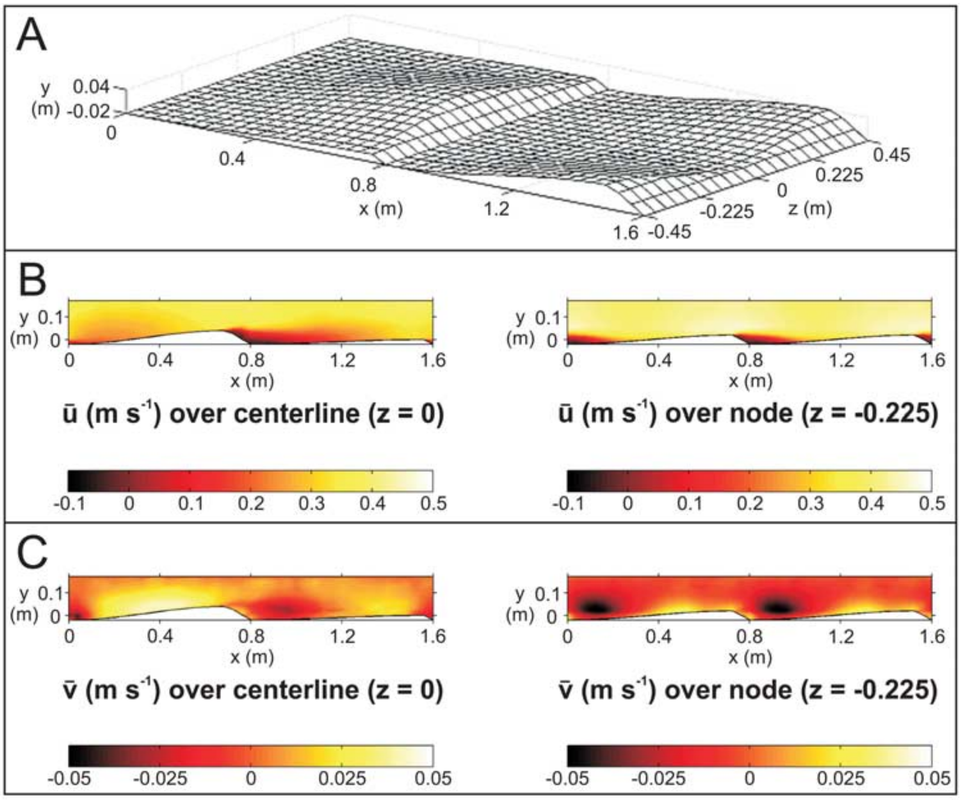


**Figure 5.** Flow over 3-D dunes [from *Maddux*, 2002; *Maddux et al.*, 2003a, 2003b]. (a) Schematic diagram of the 3-D fixed dune morphology, illustrating lateral changes in crestal height and alternate high and low points of the crestal maximum. (b) Mean streamwise velocity (m $s^{-1}$) over the centerline (left) and node (right) of the 3-D dunes. (c) Mean vertical velocity (m $s^{-1}$) over the centerline (left) and node (right) of the 3-D dunes. Results are for the shallow water model of *Maddux* [2002] and *Maddux et al.* [2003a, 2003b], where relative dune roughness (d/Y) $\sim$ 0.23 (using mean dune height at crest d = 0.04 m and flow depth Y = 0.173 m).

[15] *Venditti* [2003] has also conducted detailed laboratory experiments with dunes of differing crest line curvature, but constant height and cross-stream sectional 2D shape (Figure 6). These results have suggested that the turbulence generated by a dune that has a convex downflow planform shape (“lobe”; Figures 6a and 6d) may be greater than the 2D equivalent (Figures 6a and 6b), and that the wake region is stronger in its downstream extent with more vigorous mixing within the flow separation zone. This lobe configuration was found to possess lower average flow velocities for a given discharge as compared to the 2D equivalent [*Venditti*, 2003]. The flow associated with the lobe was concluded to cause lateral and vertical divergence of momentum and energy, leading to a greater proportion of energy being transferred from the mean flow to turbulence, resulting in lower mean velocities but higher turbulence intensities and Reynolds stresses. In contrast, *Venditti* [2003] reports that turbulence appears to be suppressed over a single, concave down flow planform dune (“saddle”; Figures 6a and 6c), with little sign of any wake structure or developing internal boundary layer downstream of flow reattachment, and that average flow velocities here are higher than over the 2D equivalent morphology. The separation zone in the case of the saddle configuration was small, absent or weakly defined. This pattern was attributed to the convergence of flow in the hollow of these saddles that results in less extraction of energy from the mean flow, and consequently lower levels of turbulence but higher velocities. Additionally, *Venditti* [2003] reports that the characteristics of flow are also determined by whether the dune planform shapes were arranged in a regular or irregular pattern, with irregularly arranged lobes having a similar flow pattern to the saddle plan forms noted above. *Venditti* [2003] uses this feature to provide intriguing evidence and discussion that the irregular crest lines reduce drag to a greater extent than regular configurations, arguing that the transition from 2D to 3D bed forms may thus be associated with drag reduction over the bed [see also *Sirovich and Karlsson*, 1997], an implication of great relevance for predictions of form drag and sediment transport over natural river dunes. *Parsons et al.* [2005] present data on flow in a natural sand bed river with three-dimensional dunes, and conclude that dune three-dimensionality is connected to the morphology of the upstream dune, with changes in crest line curvature and crest line bifurcations/junctions significantly influencing the downstream dune form. This field study also found that dunes with lobe or saddle-shaped crest lines possessed larger, more structured, regions of vertical velocity, and smaller separation zones, than more 2D straight-crested dunes.

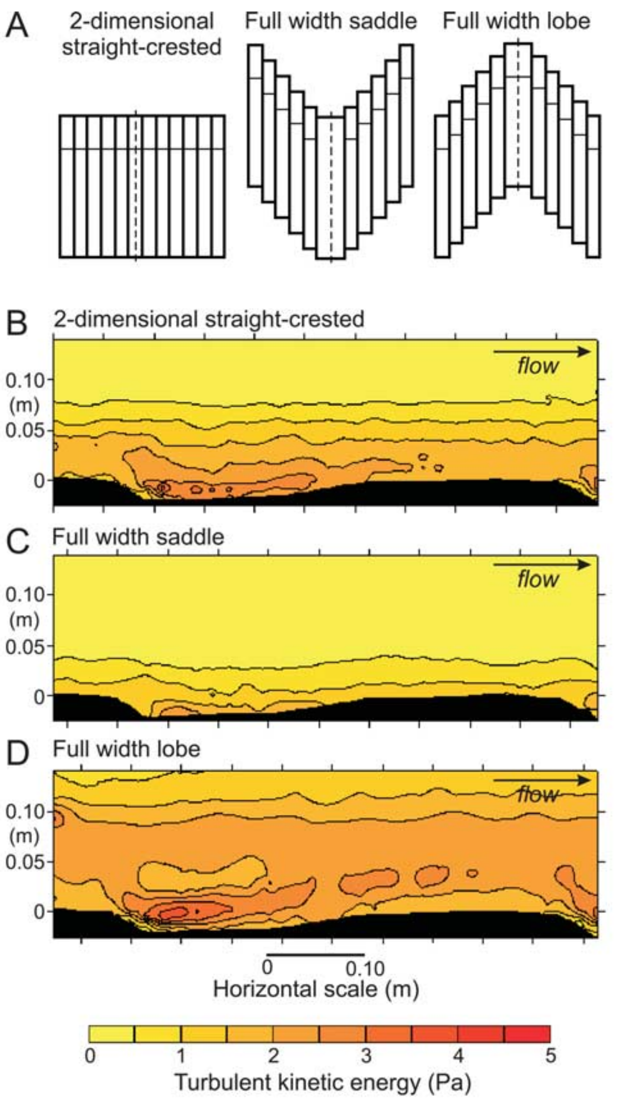


**Figure 6.** Flow over dunes with different planform crest line curvature [after *Venditti*, 2003]. (a) Definition diagram of dune curvature. Flow is from bottom to top. Patterns of turbulent kinetic energy over (b) straight-crested, (c) full width saddle, and (d) full width lobe dune configurations.

[16] It is thus clear that the nature of flow over 3D dunes is very different from many studies that have concerned 2D dunes, to the degree that the application of some of these 2D studies to the field requires careful consideration. The crest line of many natural dunes is highly curved [*Kostaschuk and MacDonald*, 1988; *Roden*, 1998; *Wilbers*, 2004; *Bartholomä et al.*, 2004; *Parsons et al.*, 2005], creating scour troughs in the dune leeside that greatly influence the leeside fluid dynamics. Field observations suggest the occurrence of intense, large-scale turbulence over such 3D forms [*Roden*, 1998; *Best et al.*, 2005] and highlight the urgent requirement for a fuller analysis of dune three-dimensionality in both laboratory and field studies. Now that studies have begun to demonstrate that the influence of 3D form can be tackled in the laboratory and field, it is opportune to revisit the types of 3D form modeled by *Allen* [1968] (Figure 4) to assess the nature of flow over these more natural bed form shapes. If the intensity of turbulence is intrinsically linked to the 3D planform, as suggested by the work of *Maddux et al.* [2003a, 2003b] and *Venditti* [2003], then future studies should seek to quantify this link, and its feedback to bed morphology, over a range of 3D planform shapes. Furthermore, the nature of bed form three-dimensionality must be quantified in order to assess the accuracy with which bed form profiles and dune migration rate can be utilized to estimate bed load sediment transport [e.g., *Engel and Lau*, 1980; *Mohrig and Smith*, 1996; *Vionnet et al.*, 1998; *Dinehart*, 2002; *Kostaschuk and Best*, 2005]. Attempts to utilize the preserved dimensions of dune cross sets to reconstruct paleoflow depths [e.g., *Leclair*, 2002] may also be complicated by significant dune three-dimensionality, which will thus produce different leeside heights for one bed form. In this case, the links between the probability density functions for preserved set thickness and formative dune height may require adjustment to account for potential dune three-dimensionality. The link between bed form three-dimensionality and flow field is thus perhaps one of the key issues that requires urgent research to advance our understanding of bed form dynamics at a wide range of spatial scales.

### 3.3. Bed Form Superimposition, Amalgamation, and the Stability of Dunes

[17] Records of bed morphology from natural channels show the frequent occurrence of dunes of different scales [*Allen and Collinson*, 1974; *Allen*, 1978; *Rubin and McCulloch*, 1980; *Harbor*, 1998; *ten Brinke et al.*, 1999; *Wilbers and ten Brinke*, 2003; *Wilbers*, 2004; *Parsons et al.*, 2005] (Figure 7), possibly as a response to both nonuniform and unsteady flow, hysteresis effects within a flood hydrograph, or the developing internal boundary layer on the stoss side of large dunes. Records of dune morphology from many rivers (Figure 7) show the occurrence of smaller dunes superimposed on the stoss side of larger dunes, with some low-angle leesides also possessing superimposed dunes (Figure 7b). Multibeam echo sounding (Figure 7c) also now permits full quantification of the nature of this superimposition, showing both the changing wavelength of the superimposed dunes on the stoss side of the larger dune, and the three-dimensional planform of these smaller bed forms. The superimposition of dunes of different scale will also play a vital role in the periodic supply of sediment to the crest of the large dune, and will thus determine the temporal fluctuations in leeside avalanching and cross-set formation, a point noted for "sand sheets" migrating over dunes by *Venditti et al.* [2005a]. The exact nature of dune-leeside deposits may thus hold a precise record of the superimposed bed forms that have migrated over their stoss sides, and there is great potential to further exploit this attribute of dune superimposition to refine our reconstruction of paleo-bed-form dynamics. The rate of bed form migration is largely a function of the size of the bed form and volume of sediment that has to be transported, with smaller bed forms possessing higher rates of migration [*Raudkivi and Witte*, 1990; *Ditchfield and Best*, 1992; *Coleman and Melville*, 1994; *Venditti et al.*, 2005b]. However, *Ditchfield and Best* [1992] also highlighted that the position of one bed form in relation to another is important and that erosion of the crest of one bed form, as

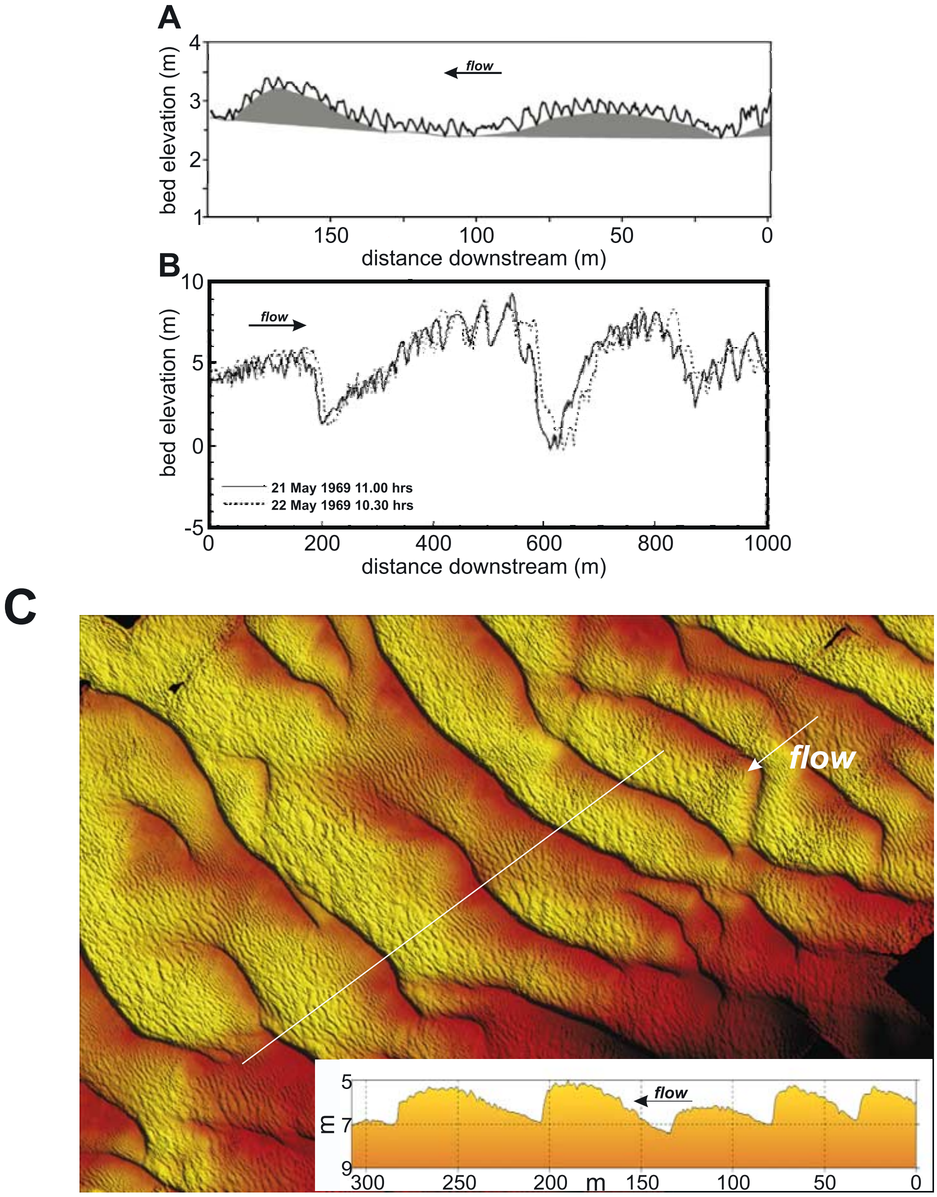


**Figure 7.** (a) Dune superimposition in the River Waal, showing dune superimposition of smaller dunes on the stoss and lee sides of the larger dunes (highlighted in gray [after *Wilbers*, 2004]) (b) Superimposition of small dunes upon large compound dunes in the Mississippi River [after *Harbor*, 1998]. The water surface is at 27 m. (c) Multibeam echo sounder image of dunes in the Paraná River [see *Parsons et al.*, 2005], illustrating the three-dimensional form of the crest lines and the ubiquitous superimposition of smaller 3-D dunes upon larger 3-D dunes. Inset shows longitudinal profile along the line indicated on the 3-D image.

a result of amalgamation with an upstream (faster moving) bed form can cause crestal scour, leading to the new "combined" bed form having a height lower than the sum of the two forms before amalgamation. This process, involving ripples superimposed on a larger bed form, has also been noted by *McCabe and Jones* [1977] as leading to the generation of convex upward reactivation surfaces within cross sets and by *Rubin* [1987a, 1987b] as being able to generate scalloped cross bedding. *Allen and Collinson* [1974] related superimposition of bed forms upon dunes to rivers in which the flow changes rapidly in time, and speculated that only one size of dune may be active at any one time. However, much work has demonstrated both that superimposition is present in most rivers, regardless of the fluctuations in hydraulic variables, and that dunes of all scale may be active at the same time [e.g., *Roden*, 1998; *Harbor*, 1998; *Parsons et al.*, 2005].

[18] Such bed form superimposition, and subsequent bed form amalgamation, induces substantial changes to the flow field during the processes of amalgamation [*Best and López*, 1998; *Fernandez*, 2001; R. Fernandez et al., Mean flow, turbulence structure and bedform superimposition across the ripple-dune transition, submitted to *Water Resources Research*, 2005, hereinafter referred to as Fernandez et al.,

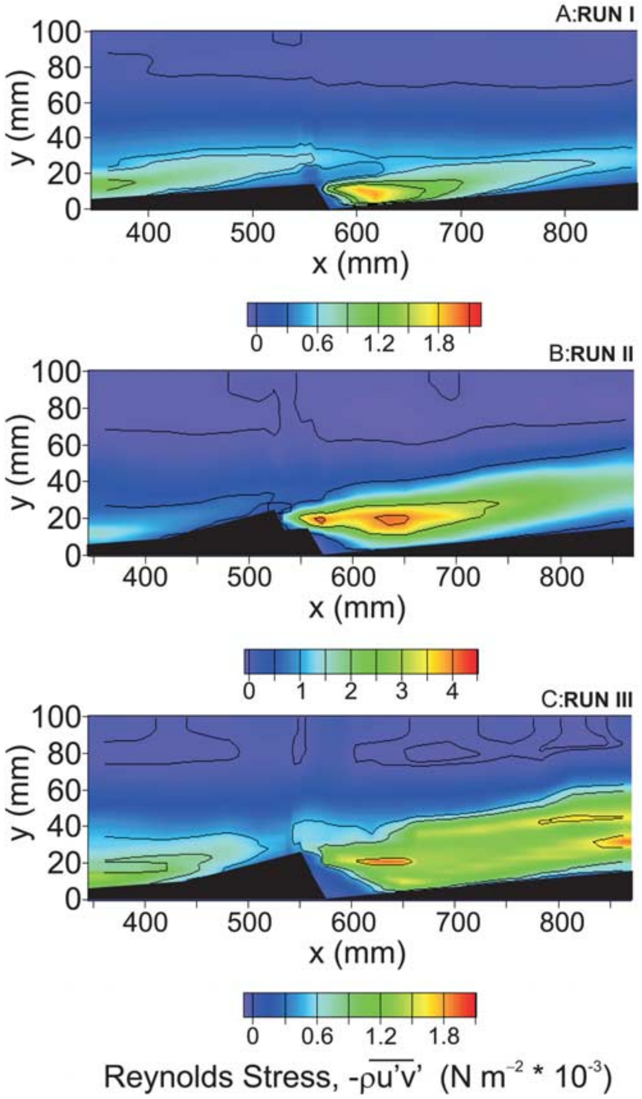


**Figure 8.** Plots of Reynolds stress, $-\rho\overline{u'v'}$, at three different stages of bed form amalgamation over fixed triangular ripples [after *Fernandez*, 2001; Fernandez et al., submitted reference, 2005], (a) Run I: ripple. (b) Run II: ripple with smaller ripple nearing crest. Note the higher Reynolds stress values and differing scale range. (c) Run III: flow with both bed forms amalgamated into a state representative of a dune.

submitted reference, 2005]. Simple flume experiments with fixed bed forms, examining the differing flow fields present as a smaller bed form is located at different positions along the stoss side of a larger bed form (Figure 8) [*Best and López*, 1998; *Fernandez*, 2001; Fernandez et al., submitted reference, 2005], show distinct changes in mean flow as the bed forms amalgamate. Plots of the $-\rho\overline{u'v'}$ Reynolds stress (where ρ is the fluid density; Figure 8) associated with each of these states, illustrate that the maximum Reynolds stresses are generated by the forms as they near amalgamation (Figure 8b), and not once they have combined. This feature is likely attributable to the interaction of the flow in the leeside of each bed form, and in particular the interaction of the shear layer formed on the smaller bed form leeside with that downstream over the larger form. Figure 8 also demonstrates why crestal erosion of the larger form is common just before amalgamation is complete [cf. *Ditchfield and Best*, 1992; *McCabe and Jones*, 1977]: the higher stresses caused by flow separation from the upstream bed form cause increased erosion and lowering of the height of the larger downstream form. Such processes may thus be responsible for producing reactivation surfaces in the dune leeside under a steady flow, but in which dune superimposition produces a succession of smaller forms migrating over the stoss side of the dune. The interaction between adjacent flow fields, and modulation of one flow field by another, is clearly a feature that will be present over not only all dune covered beds, but all beds with multiple form roughness: furthermore, the differing size and celerity of bed forms will make this interaction highly complex. For instance, *Sukhodolov et al.* [2004] highlight how the stacked wake structure present over dunes was disrupted by the presence of superimposed bed forms. A key issue for future research is how this flow field modulation occurs, how it is controlled by bed form size, morphology and spacing, and importantly how this affects both sediment transport and bed form stability. These processes may be especially important near the transitions between bed forms. For instance, the ripple-dune transition may be associated with production of a larger than average bed form that subsequently triggers large-scale flow separation and downstream erosion [*Bennett and Best*, 1996; *Best*, 1996; *Robert and Uhlman*, 2001]: a key question is how this occurs and if the interaction between flow fields of amalgamating bed forms reaches a threshold where downstream erosion and sediment transport are enhanced, thus leading to growth of a larger bed form. *Schindler and Robert* [2004] have shown statistically significant increases in suspended sediment concentration across the ripple-dune transition and reason these are related to the increasing importance of the separation zone shear layer and more influential wake region, confirming the earlier assertions of *Bennett and Best* [1996]. *Schindler and Robert* [2005] have further argued that the transition from 2D to 3D bed forms is critical in affecting turbulence across the ripple-dune transition. Further research is needed to quantify the dynamics of fluid and sediment across this transition, and their role in dune growth. Additionally, the role of possible bed form amalgamations, and flow field interactions at the dune–upper stage plane bed transition, may be important in causing flattening of the primary dune height as flow velocities and near-bed sediment concentrations increase, and require further investigation.

### 3.4. Scale and Topology of Dune-Related Turbulence and Interactions With the Flow Surface

[19] A common observation in natural river channels is the eruption of dune-related turbulence on the flow surface, this generating large-scale upwellings and boils. Laboratory [*Müller and Gyr*, 1983, 1986; *Nezu and Nakagawa*, 1993; *Kadota and Nezu*, 1999; *Gyr and Kinzelbach*, 2004; *Best*, 2005] and field research [*Matthes*, 1947; *Korchokha*, 1968; *Jackson*, 1976; *Kostaschuk and Church*, 1993; *Babakaiff and Hickin*, 1996; *Best et al.*, 2001] has also illustrated the link between these vortices and dunes, yet little is known of the topology of these coherent flow structures and how they approach, and interact with, the flow surface. The role of

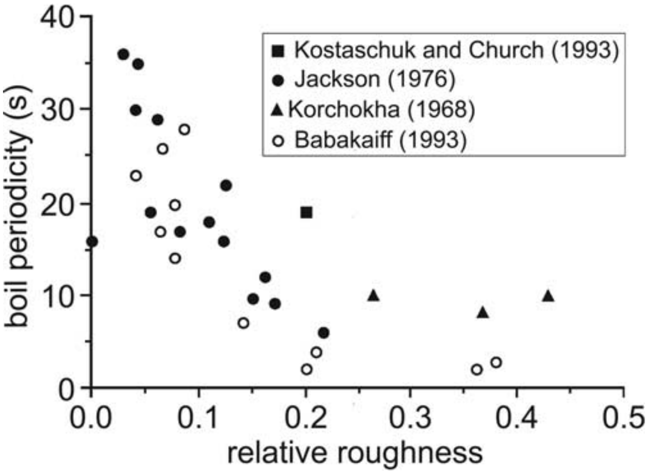


**Figure 9.** Boil periodicity as a function of the relative roughness of dunes (relative roughness = dune height/flow depth), illustrating more frequent boils occur as dunes occupy a greater fraction of the flow depth [after *Babakaiff and Hickin*, 1996].

such dune-related large-scale turbulence in the transport of sediment has been illustrated by *Itakura and Kishi* [1980], *Kostaschuk and Church* [1993], *Lapointe* [1992, 1996], *Rood and Hickin* [1989], *Schmeeckle et al.* [1999], *Venditti and Bennett* [2000], and *Cellino and Graf* [2000] and also invoked in several studies as being important in dune formation and stability [e.g., *Jackson*, 1976; *Yalin*, 1992; *Bennett and Best*, 1996; *Schindler and Robert*, 2004, 2005]. *Babakaiff and Hickin* [1996] suggested that the size and intensity of the upwelling is related to the dune height and relative form roughness, and highlighted that the generation of turbulence may increase as distinct scour pits are formed. They summarized data from several studies (Figure 9) that illustrated boil periodicity was longest at low relative roughnesses, and that once relative roughness exceeded ~0.2 (i.e., dune height >0.2 flow depth) then the boil period became constant, this suggesting that boils are more frequent at these higher relative roughnesses. *Babakaiff and Hickin* [1996] also noted that the more ''chaotic'', violently erupting boils (that they termed a ''cauliflower'' structure due to the form of the upwelling) were only present when the relative roughness exceeded 0.17. *Lapointe* [1992] also qualitatively linked boil intensity to relative roughness while *Gabel* [1993] related the size and intensity of surface boils to the curvature of the dune crest line. It is evident therefore that large-scale turbulence is characteristic of flow over many river dunes and that the surface expression of this turbulence is apparently stronger at higher dune relative roughness and with greater curvature of the crest line.

[20] Several studies [*Müller and Gyr*, 1983, 1986; *Kadota and Nezu*, 1999; *Le Couturier et al.*, 2000] have proposed that these large-scale turbulent events take the form of a ''loop'' or horseshoe-shaped vortex (Figure 10), with *Kadota and Nezu* [1999] suggesting that the vortices generated along the separation zone have a slightly different morphology to those that arise at the reattachment region (Figure 10). Some studies have also illustrated the morphology of this large-scale turbulence as it erupts on the water surface [*Coleman*, 1969; *Jackson*, 1976; *Babakaiff and Hickin*, 1996], with recent numerical simulations also illustrating the possible internal motions within these rising vortices [*Yue et al.*, 2003, 2005a, 2005b; *Hayashi et al.*, 2003]. Additionally, recent research has illustrated the key interactions that may occur between vortex rings with a free surface [*Rashidi and Banerjee*, 1988; *Rood*, 1995; *Sarpkaya*, 1996; *Kumar et al.*, 1998] and how this may influence the dynamics of the vorticity. Consideration of this literature, and observations of natural river surfaces, thus provides clues as to the topology of dune-induced large-scale turbulence and highlights the possible significance of the interaction between large-scale turbulence and the free surface. *Best* [2005] summarized this information and observations of the water surface above dune-covered beds to propose a schematic model for the interaction of dune-related turbulence with the flow surface (Figure 11). This model indicates the stages of interaction of a vortex loop with the surface, and how this is manifested as differing upwelling motions as the boil evolves and erupts on the surface. This model shows how the initial transverse vorticity is accompanied by vertical vorticity as the boil evolves and the vortex legs of the vortex loop attach to the surface, this pattern being common in many natural rivers. Importantly, *Best* [2005] also argues that this upwelling and flow surface interaction must induce subsequent downwelling toward the bed in order to satisfy flow continuity. *Best* [2005] presents laboratory particle imaging velocimetry (PIV) data to support this contention and argues that this interaction between advecting vortices and subsequent inrushes of high-velocity fluid toward the bed will be vital in sediment transport.

[21] Recent numerical modeling by *Yue et al.* [2003, 2005a, 2005b] [see also *Balachandar et al.*, 2002] has also shown the nature of this surface interaction. Using large eddy simulation and the level set method to allow simulation of the free-surface, *Yue et al.* [2003, 2005a, 2005b] investigated the origins of dune-related turbulence and the vectors patterns of flow as vortices approached the water surface. These simulations examined flow over a 0.02 m high dune in flow depths of 0.065 and 0.132 m (relative roughness ~0.31 and 0.15 respectively), and with a fixed and deformable free surface, and beautifully illustrate the likely form of vorticity and flow surface interactions (Figure 12). Several key points emerge. First, flow over the dune possesses a distinct leeside separation zone (Figure 12a) and vorticity downstream of the dune is dominated by quadrant 2 and 4 events (Figure 12b), with the simulations demonstrating that the quadrant 2 upwellings may reach the flow surface in shallow flows where the dune height was 3.24 times the dune height. These simulations also match well the measurements presented by *Best* [2005] that show an alternation of Q2 and Q4 events, and illustrate the inrush of Q4 events toward the bed following Q2 ejections. Second, slices of the numerical domain near the free surface (Figure 12c) show that flow is characterized by a series of upwellings (U) and downwellings (V) which are also associated with water surface elevation and depressions respectively in the free surface model [*Yue et al.*, 2003, 2005a, 2005b]. The simulations also depict (Figure 12c) single vortices (V) with a vertical axis of rotation, with *Yue et al.* [2003,

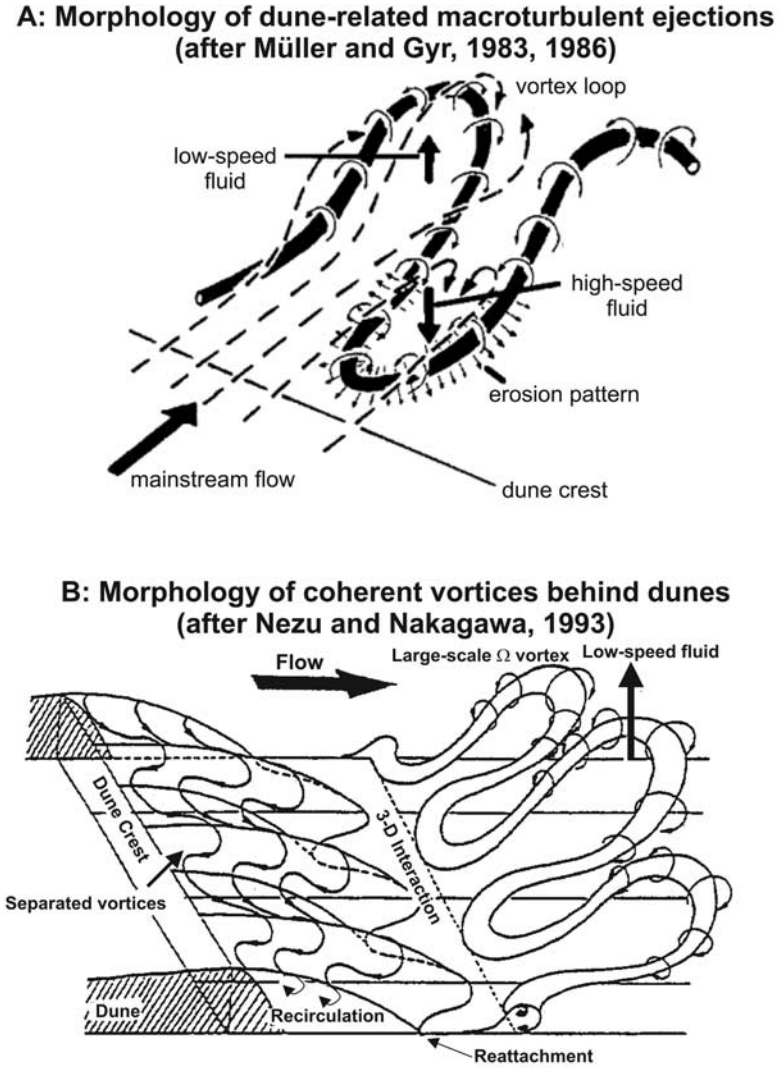


**Figure 10.** Models of vortex topology associated with dunes proposed by (a) *Müller and Gyr* [1983, 1986] and (b) *Nezu and Nakagawa* [1993].

2005a, 2005b] stating that the vortex pairs appear to be located in regions of downwelling. These simulations bear a striking resemblance to past qualitative pictures of surface boils above natural dune covered river beds [*Jackson*, 1976; *Babakaiff and Hickin*, 1996; *Best*, 2005] and provide a powerful method by which to further investigate the nature of coherent fluid motions associated with dunes. *Hayashi et al.* [2003] also show the presence of hairpin-shaped vortices in their DNS model results of flow over dunes, and found vortex topologies that showed both a normal and "reverse" hairpin shape (with the hairpin head near the bed). *Yue et al.* [2003, 2005a] also show how such dune-related vorticity interacted strongly with the flow surface where the dune height:flow depth ratio was 0.31, but that this interaction was far weaker in deeper flows when this ratio was 0.15. This matches well with the observations of *Babakaiff and Hickin* [1996] (see Figure 9 and discussion in section 3.4), who only found violent boils on the water surface at relative roughnesses >0.17, and also begins to provide support from numerical modeling for the experimental data and speculations of *Bennett and Best* [1996] regarding the transition from ripples to dunes (see section 3.3). In addition to vortices that have a very strong spanwise vorticity, these simulations also revealed the presence of vortices that have a more elongate structure and are oriented in a streamwise direction [*Yue et al.*, 2003, 2005a, 2005b], features also found in the DNS modeling of *Hayashi et al.* [2003]. These results are also supported by other recent numerical modeling [*Zedler and Street*, 2001] that suggests that longitudinal Görtler vortices (streamwise vortices that have their axis parallel to flow [*Sherman*, 1990]) may be associated with bed forms. Clearly, although transverse vorticity is vital, interactions between vortices and a three-dimensional dune form (see section 3.2 and Figure 4) will induce both streamwise and spanwise vorticity: this subject of vortex generation, growth and interaction, with adjacent vortices, water surface and erodible bed, is an area that demands urgent attention. There is also a need to quantify the quantity and caliber of sediment entrained by such dune-generated coherent turbulent structures, and how interactions with the free surface may affect this sediment

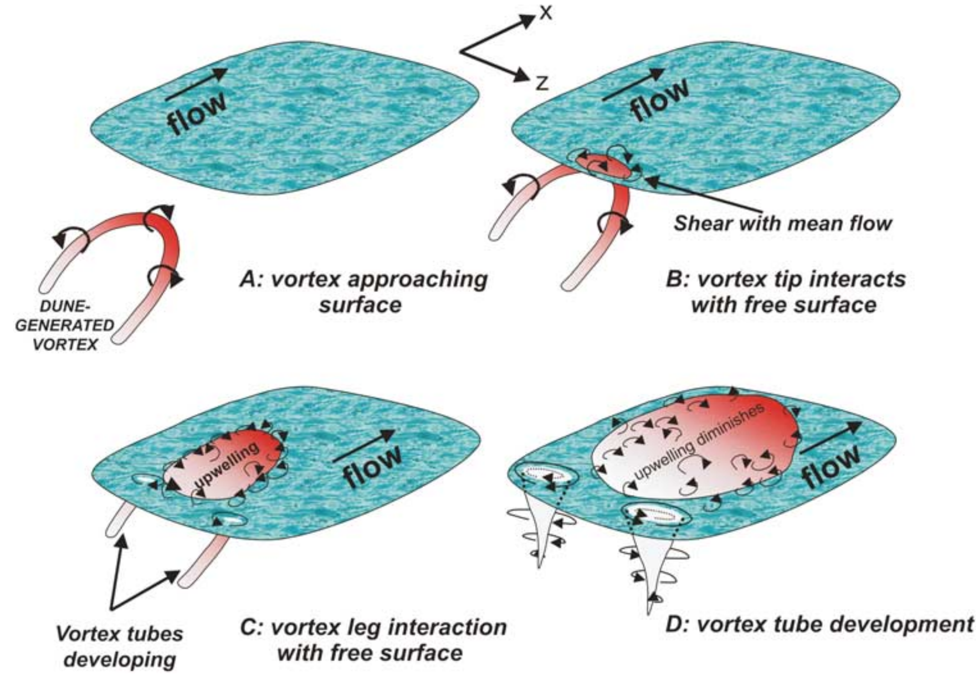


**Figure 11.** A schematic model of flow illustrating the interaction of dune-related macroturbulence with the water surface. This three-dimensional sketch illustrates the various stages of interaction of the boil with the flow surface, which will also be associated with the inrush of fluid back toward the bed [after *Best*, 2005].

dispersal. Studies on the influence of an ice cover on the flow structure associated with dunes [*Smith and Ettema*, 1997; *Ettema et al.*, 1999] form a fascinating case in which dunes form under a fixed lid, and may help shed light on the importance of the free surface. *Ettema et al.* [1999] indicate that when compared to identical dunes present under a free surface flow, the presence of an ice cover reduced the downstream distance required for dune-related boils to reach the upper surface of the flow, but that the boils were more frequent. *Ettema et al.* [1999] attributed these features to the increased velocity present under the ice cover at a constant flow discharge and the fact that more boils could be readily observed reaching the surface. However, this work did not indicate any clear influence of the fixed cover upon the rate of suspended sediment transport, and further research is needed to detail the effects of a fixed lid on dune flow structure and sediment transport.

### 3.5. Influence of Suspended Sediment on Dune Morphology and Flow Dynamics

[22] Most laboratory studies of dunes, over both fixed and mobile beds, and investigations in the field have examined situations where the water flow is clear or possesses low concentrations of suspended sediment. However, research in the field has suggested the possible link between sediment suspension and the production of low-angle dunes [e.g., *Smith and McLean*, 1977a; *Kostaschuk and Villard*, 1996; *Amsler et al.*, 2003] and the transition from dunes to upper stage plane beds has also been linked to the increasing effect of suspended bed sediment [*Kikkawa and Fukuoka*, 1969; *Engelund and Fredsøe*, 1974; *Fredsøe and Engelund*, 1975; *Smith and McLean*, 1977a; *Wan*, 1982; *Bridge and Best*, 1988; *Nnadi and Wilson*, 1995]. Data from natural channels indicate that the form of dunes becomes lower and flatter as the suspended load:bed load ratio increases (Figure 13), a contention also made in the seminal paper of *Smith and McLean* [1977a]. However, it is also apparent that in some natural channels the height and steepness of the dunes increases at higher transport stages [e.g., *Roden*, 1998; *Amsler and Schreider*, 1999; *Amsler et al.*, 2003], suggesting that suspended sediment concentration may not be the only variable influencing bed form flattening. For instance, bed form amalgamation has been shown above to lead to local flattening of the dune crest during the amalgamation process and this, together with the influence of hysteresis effects [*Allen*, 1978; *Amsler and Schreider*, 1999] and sediment concentration, may also be vital. Additionally, laboratory experiments indicate that at certain clay concentrations the dune morphology may be significantly modified (Figure 14a) [*Wan*, 1982] dependent on the clay concentration, clay type (and hence fluid viscosity) and applied shear rate. *Wan and Wang* [1994] show how the stability field of dunes is influenced by clay concentration, with dunes becoming increasingly replaced by upper stage plane beds at higher volumetric clay concentrations (Figure 14b). Since sediment concentrations in some natural rivers may reach high values, such as 1500 g $L^{-1}$ in the Huanghe [*Wan and Wang*, 1994] and 100 $gL^{-1}$ in the Rio Bermejo, Argentina [*Amsler and Prendes*, 2000], it is likely that dune morphology and flow resistance will be markedly different in many channels with high sediment concentrations. Recent work examining flow with a transitional behavior between turbulent and laminar [*Baas and Best*,

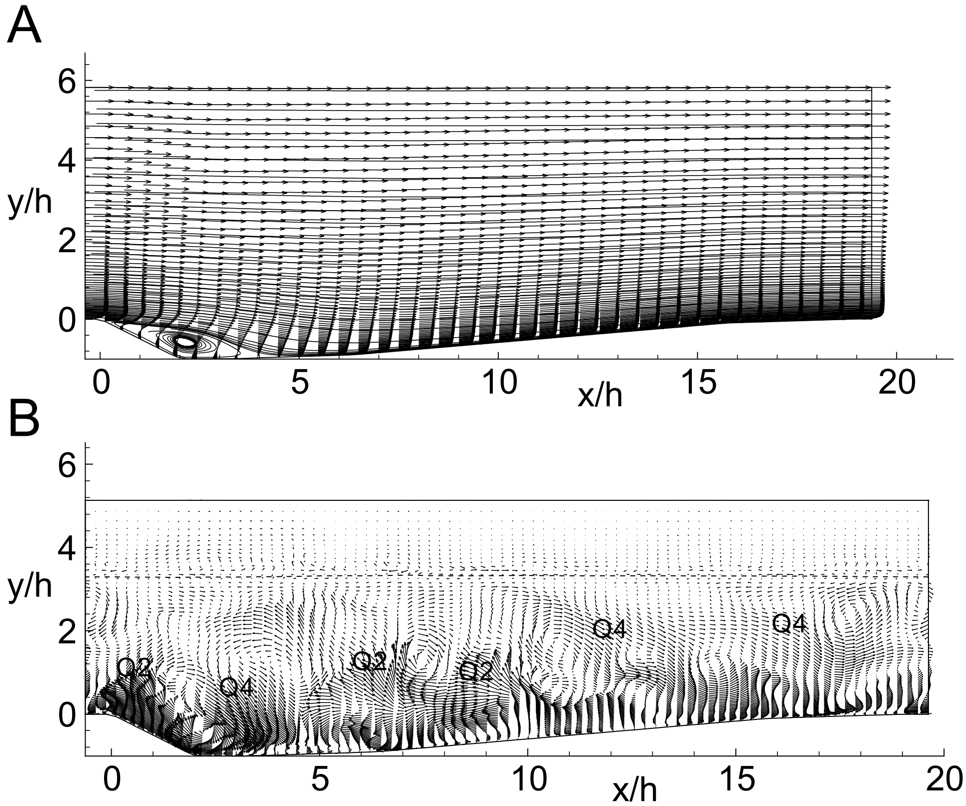


**Figure 12.** Results of a numerical simulation of flow over dunes (data courtesy of W. Yue [see *Yue et al.*, 2003]). Here x, y, and z refer to the downstream, vertical, and cross-stream planes, respectively (corresponding to the u, v, and w velocities), and h is the dune height at the crest. (a) Time-averaged velocity vectors and streamlines over a dune modeled with a plane free surface, illustrating the zone of flow separation in the dune leeside. Flow is left to right. (b) Simulation of flow with a freely deformable water surface, illustrating the instantaneous velocity fluctuations u′ and v′, at one time step in the model. The instantaneous fluctuations have been normalized by the free surface velocity and reveal a series of quadrant 2 (Q2) and quadrant 4 (Q4) events. (c) Top plot: top view of the free surface above the dune shown in Figure 12a, at one time step in the simulation [after *Yue et al.*, 2003, Figure 5.29], illustrating the u-w velocity vectors, together with two planes of instantaneous flow across the width of the dune (middle and bottom plots). Planes shown in middle and bottom plots are taken from z/h = 4.9 and 2.3, respectively (see dotted lines in top plot for location of sections). Flow is left to right in all plots. The vectors are drawn with the mean downstream surface velocity subtracted from the downstream velocity at each point in order to better illustrate the vortical motions. Vectors pointing upstream thus depict downstream velocities less than the free surface mean velocity, whereas arrows directed downstream are greater than this mean. Vectors in the top plot are proportional to velocity, whereas the vectors in the middle and bottom plots are of equal length in order to better portray the fluid motion. Areas of red and blue (contoured) are regions of positive and negative vertical velocity respectively, illustrating zones of upwelling (U) and downwelling (D). Figure 12c also shows the presence of vertical vortices (V) and reveals features similar to those observed on the free surface of natural rivers with dune-covered beds (see Figure 12c, top). Also note the association of regions of upwelling and downwelling, similar to observations in the laboratory study of *Best* [2005].

2002] has demonstrated how this transition may occur at far lower clay concentrations than previously assumed. Although clay type, grain size distribution and applied shear will be critical in determining the exact response of the flow, it is clear that many assumptions regarding the existence and stability of dunes require revision at higher suspended sediment concentrations. Recent work using nonintrusive ultrasonic Doppler profiling [*Baas and Best*, 2002] provides a methodology for achieving this, and preliminary results show that flow separation may be absent over dune-scale roughness at higher (~ 8% by volume) sediment concentrations [*Best et al.*, 2000].

[23] Thus since high sediment concentrations are often present in alluvial channels, the links between sediment concentration and turbulence modulation over dunes, and the subsequent effects on dune morphology, require urgent investigation. These investigations need to encompass both the beginnings of feedback between flow and sediment concentration, manifested by the onset of drag reduction [*Gust*, 1976; *Best and Leeder*, 1993; *Li and Gust*, 2000]

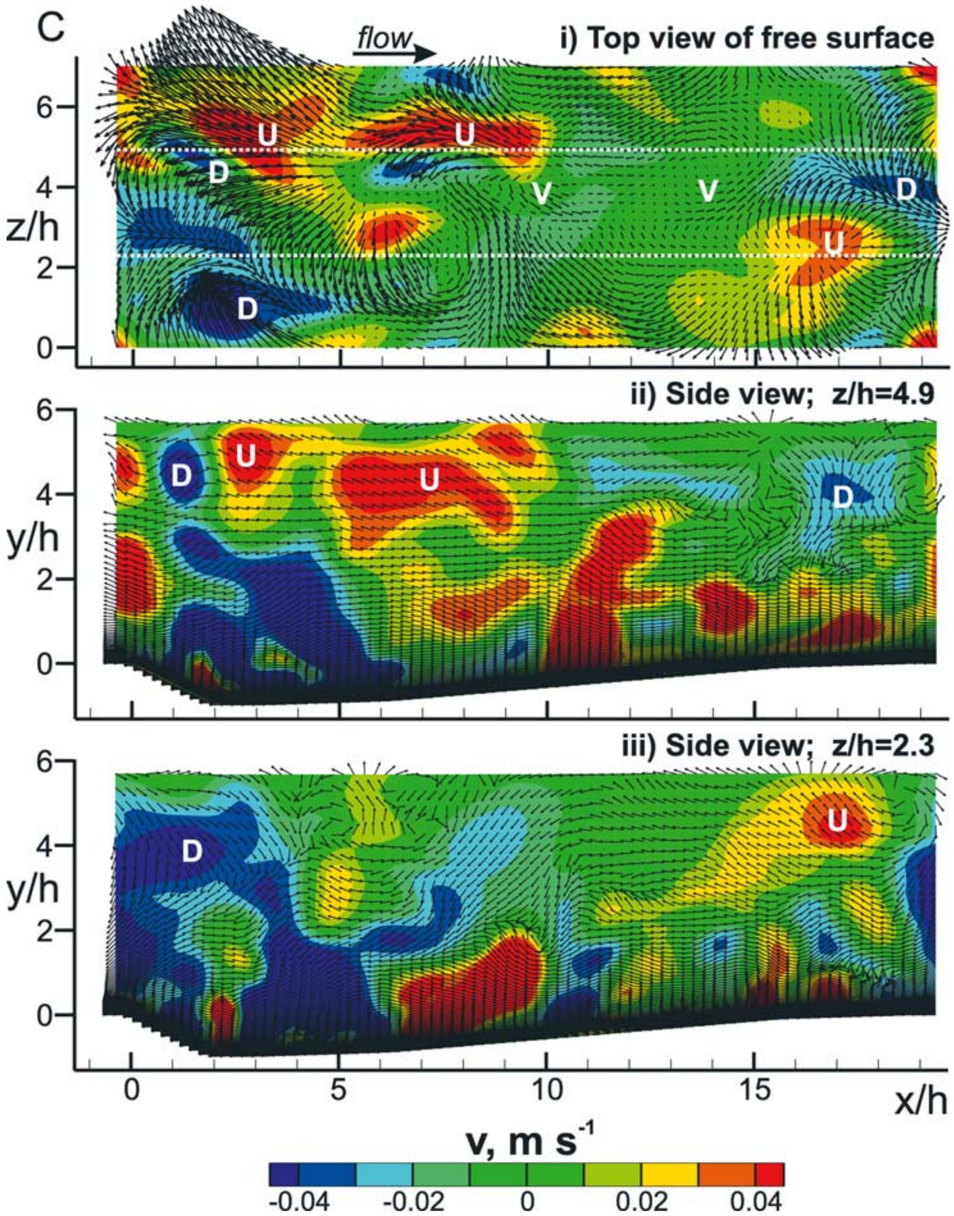


**Figure 12.** (continued)

through to the transition to increasingly non-Newtonian flow behavior [*Baas and Best*, 2002]. These investigations must document the nature of flow modulation across this transition in relation to a wide range of boundary conditions, including grain size and turbulence scale [*Gore and Crowe*, 1989a, 1989b, 1991; *Hetsroni*, 1989, 1993; *Kulick et al.*, 1993, 1994; *Crowe*, 1993; *Yarin and Hetsroni*, 1994a, 1994b; *Bolio and Sinclair*, 1995; *Crowe et al.*, 1996; *Elghobashi*, 1994], sediment concentration [e.g., *Elghobashi and Truesdell*, 1993; *Elghobashi*, 1994; *Crowe et al.*, 1996; *Baas and Best*, 2002], grain size/sorting and applied shear rate/flow velocities. Past research that has linked dune flattening to developing stratification within the flow due to increased sediment suspension [*Smith and McLean*, 1977a], and also the phase shift between the bed form and local rate of sediment transport [*Engelund and Fredsøe*, 1974; *Fredsøe and Engelund*, 1975; *Fredsøe*, 1982; *Wan*, 1982], also needs to be investigated further with respect to changing dune form. It is thus desirable that these future studies should be addressed through an integrated approach utilizing laboratory and numerical modeling and field quantification.

## 4. Conclusions

[24] River dunes are ubiquitous features of the fluvial landscape and adopt importance in many areas of pure and applied research, encompassing contemporary and ancient sedimentary environments. This paper has outlined some areas of ongoing research and debate and highlights the need for integrated, and most importantly interdisciplinary, studies to more fully understand the morphology and

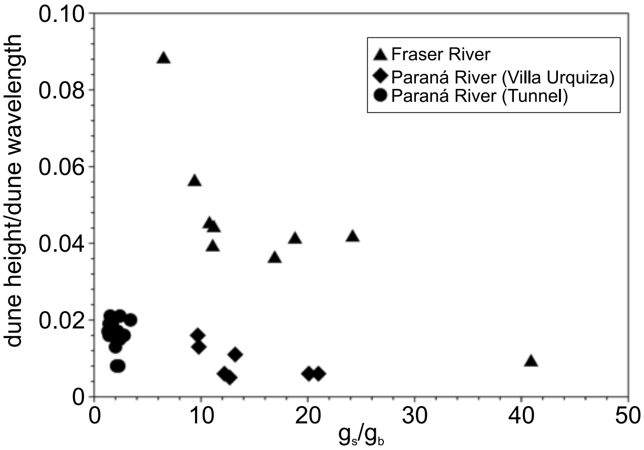


**Figure 13.** Dune morphology, expressed as the form index of dune height/dune length, as a function of the ratio between the suspended load ($g_s$) and bed load ($g_b$). Data are from the Fraser River, Canada (data courtesy of R. Kostaschuk) and the Paraná River, Argentina (data from *Amsler and Schreider* [1999]). Note how the dunes become flatter as the relative amount of suspended sediment increases, although data from the Paraná also reveal that other factors, such as temporal lag effects and the morphological geometry of the river reach, are important.

kinematics of dune morphology and flow. Two broad themes emerge for future research. First, it is clear that there is an urgent need to understand the complex relationships between bed form three-dimensionality and the associated flow field, and the role of three-dimensionality in modulating both flow and sediment transport. This must include investigations of crest line curvature, dune shape and bed form superimposition. It is clear that recent developments in field methodologies, laboratory experimentation and numerical simulations offer a powerful integrated approach to investigate these complex flow fields. Second, many past studies of dune flow dynamics have utilized clear water conditions and fixed beds that have enabled great insights into the mean and turbulent flow structure. However, future work must tackle the complexity of truly mobile beds, and the multifarious links between flow, sediment transport and developing bed morphology, at both low and high sediment concentrations. This is essential to develop empirical relationships and theoretical models that can be better applied within contemporary alluvial channels. There also appears great potential in linking the processes of surface turbulent flow over dunes with flow in the subsurface that is critical in hyporheic exchange [*Packman et al.*, 2004].

[25] Additionally, the characteristics of flow over alluvial dunes bear many similarities to flow over both tidal and oceanic bed forms, as well as to flow over aeolian dunes (see the classic text of *Bagnold* [1941], the recent review by *Walker and Nickling* [2002], and the recent studies of *Frank and Kocurek* [1996], *Parsons et al.* [2004], and *Hesp et al.* [2005]). Thus, besides research in the areas discussed herein, there is much fruitful collaboration to be achieved at the interdisciplinary boundaries between differing earth surface environments and different branches of science. For example, recent advances concerning the dynamics and origin of aeolian dunes have been accomplished through a potent mix of laboratory experimentation, field surveys and theoretical approaches, and there is clearly much scope to test, apply and amend this theory to alluvial bed forms. For instance, work on the origin and spacing of aeolian dunes and the role of crest line terminations (or defects) has produced strikingly realistic morphologies from models with relatively simple rules [e.g., *Werner*, 1995; *Werner and Kocurek*, 1997, 1999], while models for the nonlinear dynamics of dunes [e.g., *Prigozhin*, 1999] have examined bed form growth and interactions from a perspective that excludes explicit modeling of the detailed fluid flow. Research on the scaling of ripples formed in granular media [*Zoueshtiagh and Thomas*, 2000, 2003] has also suggested universal scalings for bed forms formed under rotating fluids. These studies form fascinating parallel

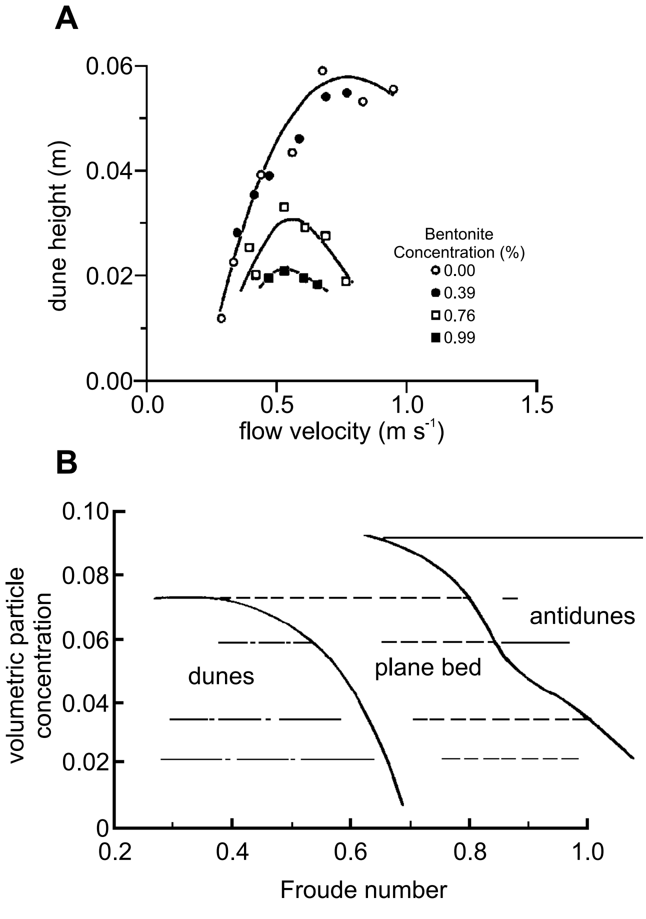


**Figure 14.** The influence of suspended sediment concentration on dune height and stability. (a) Dune height as a function of increasing volumetric concentrations of suspended bentonite. Figure 14a illustrates the lowering of dune height at higher clay concentrations and that only low-amplitude dunes exist at C = 0.99% [after *Wan*, 1982]. (b) Stability fields of dunes as a function of Froude number and volumetric particle concentration [after *Wan and Wang*, 1994]. Note the suggested absence of dunes at volumetric particle concentrations greater than ~0.08.

approaches to studying bed form properties to the fluid dynamic processes outlined herein. Additionally, experiments and models of aeolian sand particle transport have yielded new insights into the origin and morphology of barchan dunes [e.g., *Hersen*, 2004; *Hersen et al.*, 2002, 2004; *Endo et al.*, 2004]. The use of continuum granular flow models has also recently been utilized by *Jerolmack and Mohrig* [2005] to examine the preservation of cross sets and the influences of aggradation rate and bed form migration rate. An exciting area of research thus lies in linking the results of these studies with a greater knowledge of the fluid dynamics, and developing increasingly sophisticated numerical models for flow over complex terrain. Progress in this area thus demands fuller exploration of the links between flow structure, sediment transport as both bed and suspended load and the evolving bed topography. The prerequisite interdisciplinarity for this future research thus highlights the great utility of further meetings, such as the highly successful MARID workshops, to provide forums for discussing such ideas and fostering fuller integration between differing research communities.

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J. Best, Earth and Biosphere Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK. (j.best@earth.leeds.ac.uk)